EXPANDER FIELD REMANENT LIFE ANALYSIS AND ASSESSMENT

by
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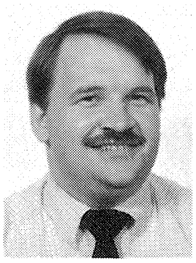

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ABSTRACT

The operating temperatures of hot gas expanders can cause degradation in the material capabilities of both the rotating and stationary components. For this reason, many of the components of the expanders are life limited. Operation beyond the design or useful life of a component can lead to inservice component failures. The determination of when the various components require replacement has been a difficult one for the operators of the equipment since the effects of high temperature operation often are not readily detectable via visual or conventional non-destructive techniques. The life of components (casings, nosecone, shroud rings, rotor blades, rotor discs, etc.) is dependent upon the individual component's operating conditions and consideration must be given to both steady and transient operation. Techniques are described along with the equipment that has been developed and utilized in several field installations to assist in the determination of the useful life of expander components. Examples of the findings from typical field life evaluations are presented. In addition to the metallurgical evaluations, the component design capabilities, service conditions, and operating history must also be evaluated. While these techniques have been developed for the fluid catalytic cracking (FCC) hot gas expander, they are directly applicable to other high temperature turbines such as gas, steam, and other expander applications.

INTRODUCTION

As the FCC expander population continues to grow, and with many of the early expanders having reached or exceeded their initial design life, the need for assessing and determining the remanent life of critical components of machines has arisen. As of Spring 1996, 108 FCC expanders have been built. Thirty or more of these expanders have exceeded 100,000 hr of operation. In addition, the higher operating temperatures (originally 1200°F (649° C), now more typically 1350° F (735° C)) are putting greater demands and reducing useful operating time on the FCC expander.

This study is directed toward expander operators that may benefit from remanent life analysis. Life assessment methods, as they apply specifically to the FCC expander, are presented. The capabilities and limitations of remaining life assessment techniques are discussed. Care must be taken to insure that a proper and complete methodology is used in any life assessment. Multiple cases have occurred in which reputable engineering concerns provided an operator with a remanent life assessments of critical components solely on metallurgical replicas taken at lightly loaded areas of a rotor disc or casing. If the equipment operator is not sufficiently familiar with remanent life methodology and capability, a false sense of security and potentially dangerous conditions could exist.

USES FOR REMANENT LIFE ANALYSIS

Remanent life assessments are performed to establish equipment operational periods, maintenance requirements, or component replacement timing. Typically, the following determinations are sought:

- Is it safe to operate the expander for another operating campaign?
- Will the expander operate until the next scheduled overhaul without requiring unplanned maintenance?
- Should the entire expander be replaced or just certain components?
- As the expander approaches, or has exceeded its design life, what component inspections are required and at what intervals?
- Do suitable life-extension treatments exist for given components; and when should they be implemented?
- When must an expander, or its major components, be replaced?
- Can the expander and/or its components be operated beyond its originally stated design life? What are the risks associated with continued operation?
- Are there changes in operation or component rework that can extend the operating life of an expander?

A remanent life analysis provides an alternative to the normally conservative life criteria established by the original equipment manufacturer, which rightfully considers worst case scenarios. Most FCC expander manufacturers have developed a specific expander frame to operate with the maximum blade length, at the maximum continuous speed and temperature for 100,000 hr. If a specific expander is not operating at the frame ratings, it is likely that many, if not all, of the components are suitable for operation in excess of 100,000 hr. In addition, many of the expander components are not operating at temperatures sufficient to cause major degradation and will undoubtedly operate for longer periods of time. A remanent life analysis allows the user to make maintenance decisions based upon actual operating history, component metallurgy, and site conditions. It also allows the user to look deeper into the future than a visual or NDT inspection of an expander allows, thus providing greater assurance of reliable operation until the next scheduled inspection.

Users of expanders require that all major maintenance be performed at scheduled unit turnaround intervals. Shutdowns for unplanned maintenance are very costly in terms of lost production. A basic tenet of preventative maintenance is to avoid unplanned shutdowns by replacing wearing components at planned intervals. In many cases this approach also avoids significant down time since expander component failure can result in extensive damage–this also raises significant safety issues. Remanent life analysis is another tool in the arsenal of an expander user that can assist him in making sound engineering decisions.

CAUSES OF COMPONENT FAILURE IN AGING GAS EXPANDERS

Remanent life analysis covers the failure of parts due to material degradation typically caused by long term elevated temperature operation. Creep, low cycle fatigue, corrosion, erosion, and the general degradation of material capabilities can be primary causes of component failures.. These phenomena are briefly reviewed later.

High temperature creep. Creep is characterized by material deformation, under stress and at elevated temperature, that can cause unacceptable dimensional changes, local creep crack growth, and in its most severe manifestation, creep rupture (separation) of the component. Within the life time of the part, creep is addressed in the component design phase by maintaining design stresses at a level where, given the component operating temperature, distortions will be acceptable and rupture will not occur. Creep is manifested by the formation of microscopic creep voids in the grain boundary area. As growth and accumulation of creep voids continue, voids join together until a critical flaw size is reached, forming a crack or cracks which lead to eventual failure. These voids are observable through optical microscopy. The formation of creep voids are shown in Figure 1 within an FCC casing subject to high operating temperatures and stresses. The density of creep voids, along with changes in microstructure, can be used to predict remanent creep life.

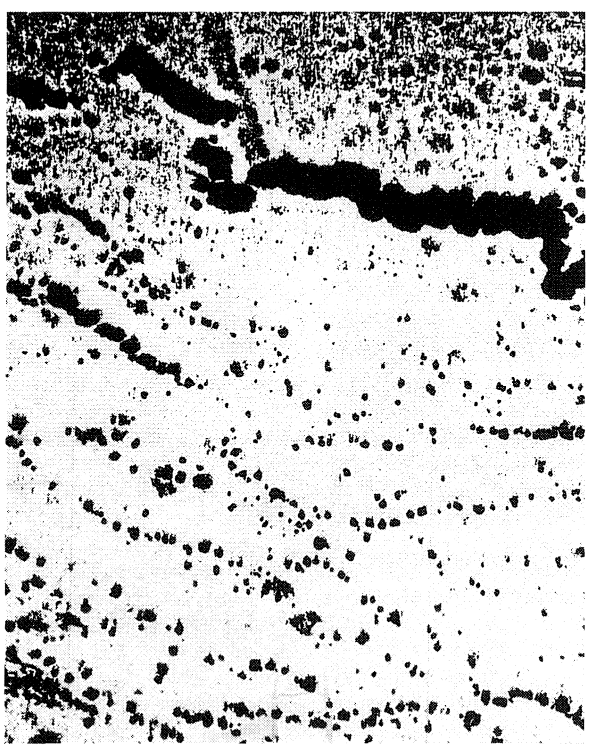

Figure 1. Example of High Temperature/Stress Creep Voids in Stainless Steel Casing.

Fatigue. Fatigue is a failure mechanism caused by the cyclical application of stresses that are below the ultimate strength level of the material.

High-cycle fatigue (HCF). In turbomachinery, high-cycle fatigue is the result of an accumulation of millions of cycles at relatively low stress levels. Causes of high cycle fatigue are: (1) varying gas bending loads due to the moving of rotating blades past stationary blade passages, and (2) resonant vibrations excited by an engine order or blade-passing frequency. Most materials have a fatigue strength threshold, called the endurance limit, below which a component will not fail regardless of the number of load cycles. Proper design practice is to limit combined stresses to such a level. On mature expanders one can assume that this is the case. Since millions of cycles can accumulate in a matter of hours, these failures typically occur early in the life of the machine and long before the ultimate design life of the expander. Therefore, high-cycle fatigue damage is not typically considered in a remaining life analysis.

Low-cycle fatigue (LCF). Low cycle fatigue is caused by relatively high cyclic stresses, near or even above, the yield strength of the material and generally in the presence of a stress concentration. These high cyclic stresses are associated with startup/shutdown cycles, major load changes, and off design operating parameter excursions (particularly temperature).

Typically, transient thermal stresses comprise the largest fraction of these cyclic stresses. Generally, the larger and more abrupt the change in temperature, the higher the stress level. In the elevated temperature range this low-cycle fatigue is also termed thermal fatigue.

Erosion. FCC expanders are subjected to continual particulate loadings that can cause severe erosion in unusual and unexpected areas in and around the flowpath of the expander. This erosion often reduces the structural integrity of critical components by significantly increasing the local stress concentrations and by decreasing the amount of load bearing material.

Erosion can effect the life of casing components, including stator vanes and rotor components. An example of the severe stress concentration that can be created as the result of catalyst erosion can be seen in Figure 2.

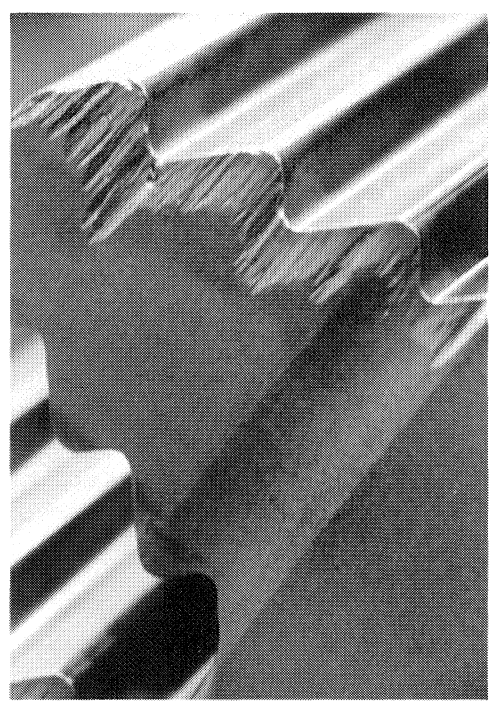

Figure 2. Rotor Disc Erosion Causing Severe Stress Concentration.

Corrosion. Expander components can experience corrosion during normal operation along with during periods of unit shutdown. The normal FCC environment contains significant levels of sulfur, salts, and heavy metals that become very corrosive to many alloys at the high operating temperatures. Corrosion often causes a pitting attack that affects the structural integrity of the rotor components and becomes a significant factor in a remaining life assessment.

Elevated Temperature Corrosion

Sulfur compounds. Corrosion by various sulfur compounds is a common problem in petroleum refining processes. At temperatures in excess of 1000°F (540°C), the sulfur activity of the gaseous environment is sufficiently high to form sulfide corrosion product. The sulfidation corrosion is related to the level of oxygen and sulfur in the flue gas. The problem is compounded with incomplete combustion operation where the low oxygen levels of the flue gas degrade and prevent the formation of protective oxide scales. The relative corrosivity of sulfur compounds generally increases with increasing temperature. The nickel base alloys are very vulnerable to the sulfur that tends to diffuse inward, forming sulfides deep in the metal grain boundaries. These finger like protrusions of sulfide may act to localize stress and reduce the load bearing capacity of the steel. Clearly, the longer the exposure to sulfur, the greater the chances of harmful sulfur attack.

Oxidation. Expander operating temperatures are sufficient to cause oxidation of low alloy, stainless, and nickel base alloys. The oxidation is more prevalent in complete combustion processes where the oxygen levels in the flue gas are typically one to two percent by weight. Like the corrosion mechanisms, oxidation can lead to serious material surface degradation and (even intergranular penetration) that lead to significant stress risers.

Shutdown corrosion. Shutdown corrosion has been significant in a number of FCC expander installations. The formation of polytheonic or other sulfur bearing acids can lead to stress corrosion cracking of the austenitic 300 series stainless steel components. This phenomena is typically related to a shutdown condition where condensation combines with the sulfur in the flue gas. Sulfur acid attack often leads to stress corrosion cracking. An expander inlet flange is shown cracked in Figure 3 as the result of stress corrosion cracking and polytheonic acid attack.

Figure 3. Stress Corrosion Cracking Resulting From Polytheonic Acid Attack.

Degradation of Material Properties

In predicting component life, or in evaluating whether a component is fit to return to service, inservice aging is a strong consideration. "Aging" refers to a group of metallurgical changes that occur in most materials through exposure to elevated temperatures for extended periods of time. Different materials react to the effects of temperature at different rates and to different extents depending upon both the chemistry and heat treatment of the alloy. Some high temperature aging effects are as follows:

Graphitization. The low alloy (typically 21/4 Cr-1 Mo) carbon steels used in early expanders for outer casings can experience a phenomena known as graphitization. When low alloy steels are exposed to temperatures in excess of 1000°F (538°C) for prolonged periods of time, the carbide phase of the steel can be converted to graphite.

Graphitization is dependent on exposure time and temperature, and occurs in virtually all environments whether or not the material is under stress, and results in a weakening of the steel. For example, a 0.17 percent carbon steel exposed to a temperature of 1000°F for 83,000 hr (9.5 years), has been found to experience a 21 percent reduction in tensile strength.

Spheroidization. Another potential source of strength reduction in low alloy carbon steel at elevated temperatures is spheroidization of the carbides. Spheroidization occurs because spheroidized microstructures are the most stable microstructures found in steel and high temperature promotes its formation.

Sigma phase embrittlement. When the austenitic and nickel base alloys used in expanders are exposed for long periods of time at temperatures between 1050°F (565°C) and 1550°F (843°C), a brittle intermetallic sigma phase precipitates into the grain boundaries and within any ferrite phase. Sigma phase contains approximately equal parts of chromium and iron. Sigma is a brittle phase that tends to form as platelets. This brittle phase can affect superalloys and austenitic stainless steels used in the gas expanders. (Note that sigma phase embrittlement is a different phenomena than sensitization, or intergranular corrosion, which occurs in a similar temperature range.) The most significant effect of sigma phase is in the loss of material ductility, fracture toughness, impact strength, and in some alloys, reduction in stress rupture and LCF strength. Normal operating loads can cause major component cracking that often "runs" during typical startup or shutdown cycles. Sigma phase embrittlement has been found in most grades of stainless steel expander casings. It has been directly attributed to nosecone weld failures and flange and casing cracking. The time of operation, along with the temperature of the components determines the rate and degree of sigma phase formation. The lack of weldability from sigma phase embrittlement has also been a major problem during repair of FCC expander casings after service. For example, the room temperature toughness may be so low that cracks will "run" or "craze cracking" will occur during repair welding due to the thermal gradients generated at the crack tip regions. Unfortunately for today's FCC expanders, sigma phase precipitation occurs most rapidly in the 1300°F (704°C) temperature range. In general, several years of operation in the sigma phase temperature range are required to precipitate five to 10 percent sigma phase in 300 series stainless steel. An expander casing with sigma phase embrittlement after only 40,000 hr of operation is shown in Figure 4.

Iron and Nickel Base Super Alloy Material Degradation–(Stator Vanes, Rotor Discs and Blades)

Super alloy aging phenomena include growth of grain boundary carbides, a coarsening of gamma prime precipitates, and the formation of sigma phase. These changes in microstructure significantly alter the material properties of the nickel-base materials. Most significant is the reduction in impact strength and fracture toughness.

Growth of grain boundary carbides. Grain boundaries of nickel-based alloys initially contain fine, discrete carbide particles. Exposure to elevated temperatures causes these particles to grow,

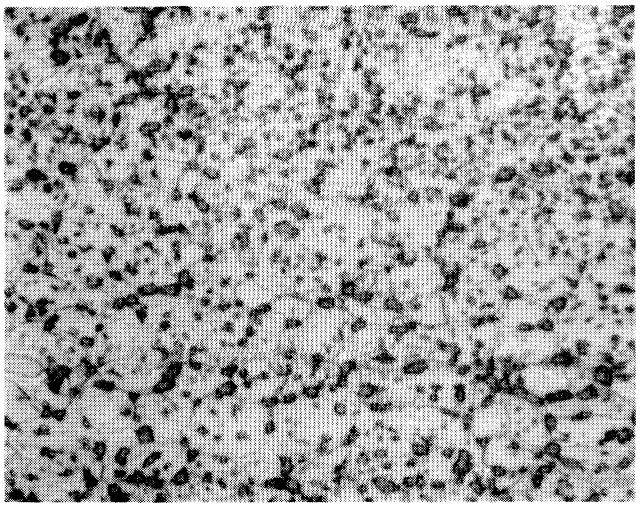

Figure 4. Sigma Phase After 40,000 hr. 347 stainless steel casing.

forming chains of large M23C6 particles. Formation of these chains has been tied to a decrease in stress rupture strength, a loss of stress rupture ductility, a decrease in thermal fatigue strength, and a loss of toughness.

Gamma prime coarsening. High strength nickel-base blade alloys typically used for rotor blades are strengthened by the precipitation of gamma prime particles (an intermetallic phase) during their age hardening heat treatment. At high temperatures and extended exposure, these particles may grow larger (coarsen). Coarsening of gamma prime precipitates can cause a reduction in both tensile and creep strength. The loss of creep strength should be accounted for when evaluating the remaining creep life of a component.

METALLURGICAL EVALUATION

Expander remanent life analysis is an attempt to predict the number of operating hours or the number of starts before failure occurs. The ability to predict remaining life implies that the metallurgical mechanisms discussed previously will degrade component life in a predictable, measurable manner. This is generally true, but predictability is a matter of degree. The accuracy with which expended life can be measured, and remaining life predicted, varies according to a number of factors, including the failure mode being investigated, the material, and the type of component. Based upon the circumstances, obtaining the desired answer may require inspection and analysis ranging from a simple visual inspection to a detailed metallurgical or analytical investigation, including material testing. The different metallurgical and analytical techniques that are employed in these analyses are presented later, along with their capabilities and limitations.

The metallurgical evaluation of the expander components is a key element of any remaining life analysis. Metallurgical analysis is used to evaluate the various damage mechanisms and the amount of degradation.

A metallurgical evaluation alone, however, cannot completely identify remaining life, particularly when considering parts that may be life-limited in a low-cycle fatigue mode. The metallographic evaluations are generally based upon more detailed microstructural analysis. Standard metallurgical analysis procedures are utilized. Samples or sample areas are prepared by polishing and etching the material to evaluate the microstructure. The areas of interest are then evaluated using conventional optical microscopes or scanning electron microscopes (SEM).

The metallagraphic data is collected in a variety of ways depending upon the component being evaluated:

In-situ metallography. The areas of interest are carefully selected to reflect the overall material condition along with those that would be most susceptible to the deleterious effects described above. In-situ metallography encompasses the cleaning, surface preparation, polishing, and etching similar to that employed in a laboratory. Chemical and electro-chemical etching procedures have been developed along with special portable field metallography equipment. The metallographically prepared regions are examined with a field microscope and prepared for replication. The field metallography is a non-destructive inspection technique.

Field microscopes and optical depth micrometers are used to evaluate material microstructure corrosion depth and penetration. Part of the field metallurgical preparation and evaluation equipment is shown in Figure 5. Typical areas evaluated during a remanent life analysis are shown in Figure 6.

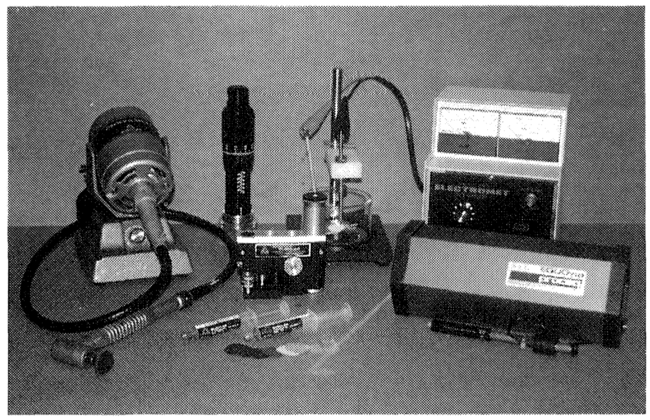

Figure 5. Typical Equipment Required for Onsite Metallography Including Optical Depth Micrometers, Field Microscope, Etching, Polishing Equipment and Hardness Tester.

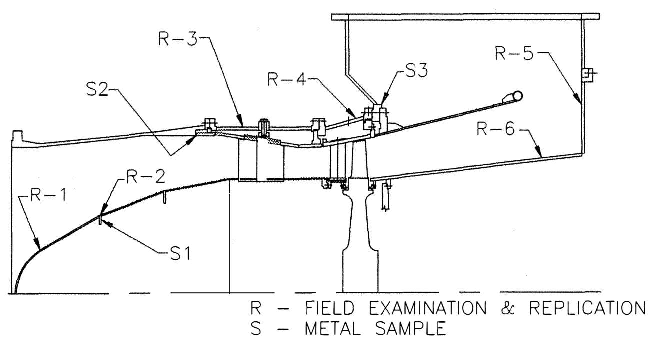

Figure 6. Typical Locations for Metallurgical Evaluations.

Replicas. Records of the in-situ metallography are obtained by taking metallographic surface replicas where specially prepared acetate strips are applied to the component surface and allowed to cure. Prior to applying the acetate, the surface of interest is polished and etched as it would be for a conventional metallographic sample. After curing on the surface, the acetate replica is carefully removed resulting in a negative image of the component microstructure down to the finest details–including grain structure and grain boundary features such as creep voids and carbides. The requirement for a properly prepared surface is critical if microstructure of the material is to be evaluated. This requirement can make it difficult to get good replicas in some critically stressed areas with complex geometries, such as blade or disc attachments, that are often the areas of greatest interest.

Acetate replicas are useful for evaluating surface microstructure along with corrosion damage (pit depth evaluation). The advantage of acetate replication is that it is truly non-destructive and can be taken at almost any location. Replicas can also be metallized to facilitate grain structure and size evaluation with a scanning electron microscope.

Boat samples. The removal of small samples of the subject component is extremely valuable for component evaluation. Small "boat hull" shaped specimens are removed by abrasive cutting methods in a location that will not affect the integrity of the part. These samples can be brought back to the laboratory for detailed metallurgical evaluation. Boat samples are useful for analyzing disks and casing components where conventional destructive testing would require the sacrifice of the part. In most, but not all, cases less critical areas typically exist, such as the outside of a casing flange, or a disk balancing ring. Removal of a small sample from these locations will not compromise the function of the part. Boat samples also allow for cross sectional examination of the surface, not possible with an acetate replica, which is useful in evaluating the depth of corrosive surface attack. The limitation of boat samples is that they obviously should not be removed from critical locations. It is, therefore, not possible to evaluate and test components in the areas most likely to fail first, i.e., those exposed to the highest combination of temperature and stress. However, because they are taken from areas of lower temperature and stress, boat samples are useful for gauging what the actual material properties or metallurgy of the part were prior to exposure. Since materials can vary significantly from part to part, this can serve to increase the accuracy of the remanent life estimate.

Standards have been developed to perform tensile and stress rupture testing on very small test bars that can be made from these small boat samples. The test specimens can be as small as 0.090 in (2.25 mm) in diameter by 0.5 in (12.7 mm) long.

Destructive testing. The destruction of parts is also a good option for detailed evaluation of the effects of aging. This is impractical for large parts, like casings or rotor discs, but can be often performed on smaller replaceable components such as fasteners, rotor blades, and stator vanes.

Evaluation of surface condition. Surface condition has an effect on the fatigue life of highly loaded components. Components such as blades and disks are thus manufactured with a very fine surface finish. During service, surface condition can deteriorate due to corrosion, erosion, or fretting. When evaluating the remaining life of critically loaded parts, surface finish must be examined and evaluated. Damage can take a number of forms, such as corrosion pits, erosion gouges, intergranular attack, and fretting wear.

Criteria are typically established for allowable damage depth, given factors such as the type of attack, location of the attack, and stress levels. A remaining life prediction is typically made by comparing actual damage depth to allowable damage depth criteria given the number of hours of operation. Criteria is established, based upon experience and fracture mechanics analysis.

For corrosion pitting, erosion, and fretting damage, depth measurement is usually made using an optical depth gauge or a metallurgical microscope. When the corrosion damage is in a location that is not readily accessible, or the part is too large for analysis, an acetate replica of the surface is made. As an aid in evaluation, the damaged topography is usually characterized using a scanning electron microscope. If intergranular attack is suspected, a sample of the component must be cross sectioned for metallurgical analysis. This analysis is especially important since intergranular attack provides prime crack initiation sites. Its presence in critically loaded components is often cause for their retirement.

Material testing. Material testing provides a direct measure of current component material properties. The necessity to estimate stress and thermal history can sometimes be eliminated. Typical tests performed are: hardness, impact, tensile (ultimate, yield, and elongation), and accelerated stress rupture. Tensile tests determine remanent strength and ductility. If strength has degraded below minimum acceptable levels, or is projected to do so, a component must be retired or reheat treated, if possible. More commonly, if ductility has fallen below a level where brittle failure is possible, action must also be taken.

STRUCTURAL ANALYSIS

A major part of the life prediction of a remaining life analysis is to understand the component loadings. Detailed design and operational knowledge are required to make life determinations. Structural analysis is one of the tools utilized to give a thorough understanding of the component loadings and the required material properties.

Structural analysis work scope. The following is the typical required scope of work to be done for a complete remanent life prediction:

- *Stage performance analysis*–A stage performance or aerodynamics analysis is performed to quantify the aerodynamic loadings, gas path velocities, pressures, primary and secondary flows, heat loading, and temperatures of the different expander components.
- *Steady-state heat transfer analysis*–The steady state heat transfer analysis is required in order to determine the highest metal temperatures.
- *Transient (startup and shutdown) heat transfer*–Transient heat transfer analysis is performed to determine the thermal gradients and to serve as thermal load input to the structural analysis due to thermal gradients. This is particularly important since typical thermal stresses can be about twice as severe during a transient at steady state.
- *Structural analysis*–Structural or stress analysis is performed to determine the nominal and detailed stress and thermal distributions in the expander components. Finite element analysis (FEA) is typically performed on all critical components. Areas of high stress concentration are investigated since they are the most prone to either HCF or LCF cracking. Cooling flow analysis may be part of the structural analysis since cooling flows can greatly affect the expander component life.
- *Fracture mechanics analysis*–The fracture mechanics analysis serves to check whether any existing cracks or flaws are safe and will not propagate to near critical size under the operating stresses during the remaining time of operation.
- *Operational data review*–The operating history and a detailed identification of the service conditions are key to a successful remanent life analysis. An extensive amount of operating data are required to perform a detailed remanent life analysis. A thorough review of the continuous operation (considering cumulative operating time), over temperature excursions, and number of startups/shutdowns of the unit needs to be performed.
- *Material properties*–In all cases, detailed knowledge and understanding of the materials in use, their fabrication, and thermal history are required.

Creep and fatigue. Structural analysis of an expander casing or rotor, in the broadest theoretical sense, allows one to predict fairly accurately material temperatures and stresses at all points in the components, and at all times during the equipment's operation. In the case of fatigue (even if stressed only briefly during a transient load cycle), areas of high stress concentration will dictate the life of a part. In the case of creep, the goal is to calculate temperatures and stresses, and to find the combination of parameters that minimizes life. The LCF analysis yields the expected number of expander starts at which cracking is likely to start occurring. The creep evaluation gives the amount of operating time at which the components will plastically deform to the point of becoming unstable and fail in a creep-rupture mode. Fatigue cracking will almost always be associated with the presence of a stress concentration, while creep will occur in a part experiencing high average stresses with respect to its material capability at the operating temperatures.

Prediction of stress rupture life. Excessive creep distortion can lead to rupture. Creep or rupture occurs in components subjected to a combination of long term service, high stress, and temperature. Creep or rupture is common in turbine blades, although it can also occur in discs, particularly in the rim area.

Prediction of low-cycle fatigue (LCF) life. Low-cycle fatigue can occur in any rotor component. It is more often associated with components that are exposed to rapid temperature variation that sets up thermal stresses. A disk in a turbine is a prime example, since its rim is exposed to the high flue gas temperatures and the bore is cooled by its attachment to the cooler shaft. Low-cycle fatigue cracks take many years to develop. They almost always develop in areas of stress concentration, where the local stresses are above the yield, thus resulting in damage being done with repeated startup/shutdown cycling. The manner in which the expander is operated is a significant contributing factor in the life of a rotor. For example, the rapid startup cycles of an expander generator set greatly reduces the life of the expander components in comparison to a conventional expander train that warms up slowly with the process.

PRACTICAL CONSIDERATIONS

Multiphase approach. It is usually most cost effective to perform a remaining life analysis in two phases. For the first phase, it is helpful to define a limited scope of inspection and analysis that can be completed without major expander disassembly, without destructive testing, and without costly detailed analysis work. Taking this approach will point out any obvious life-limiting problems without spending significant time or resources. The first phase analysis is also helpful in defining what additional testing and analysis may be required to determine the specific answers sought by the expander user. A list of what may be included in a typical phase one review is given in Table 1.

Table 1. Phase One: Typical work scope.

- Shutdown and remove expander rotor and inlet transition piece.
- Clean components to be inspected.
- Perform a thorough visual inspection and photo document the condition of all components.
- Perform a nondestructive inspection of critical components and high stress locations.
- Perform a positive material identification.
- Prepare and take metallurgical replicas of critical areas.
- Remove boat samples.
- Perform hardness surveys.
- Perform geometric inspections.
- Perform on and off site metallurgical analysis.
- Perform a structural review and analysis.
- Perform an operational review and analysis.

Completion of a phase one analysis will identify any significant aging or component deterioration, along with identifying if additional or more detailed analysis is required. Phase two analysis work might include some or all of the additional work items listed in Table 2. The exact work scope would depend on the expander user's goals and on the results achieved in phase one.

Table 2. Phase Two: Typical work scope.

Disassembly

- Complete disassembly of the rotor.
- Removal of the stator.
- Partial or complete casing disassembly inspection.
- Thorough visual, NDT, and dimensional inspection of rotor components.
- Thorough visual, NDT, and dimensional inspection of suspect casing components.

Metallurgical

- Metallurgical replicas of disassembled rotor surfaces.
- Boat sample removal from casings, stators and disks.
- Destructive testing of rotor blades and stator vanes.
- Macro and microscopic evaluation of component surfaces.
- Stereomicroscopic evaluation of component cross sections.
- SEM observation of grain structure.
- Corrosion product compound identification.
- Tensile testing
- Stress rupture testing
- Impact testing

Structural

- Aerodynamic and performance analysis
- Cooling flow analysis
- Thermal analysis–FEA
- Structural analysis–FEA
- Fracture mechanics analysis

Remaining life analysis is performed to provide valuable answers that are beyond the capabilities of traditional inspection techniques. While conventional NDT techniques can determine whether cracking is present in a component, it will not be able to predict whether the component will survive until the next scheduled inspection, or until the component is due to be replaced. Alternately, if an OEM recommends that an expander be retired after 100,000 hr of operation, a user has no justifiable basis for continued operation, unless the life of their specific expander components can be analyzed and predicted.

It is important that engineering judgement backed by experience be utilized in formulating the recommendations resulting from a remanent life analysis. The remanent life analysis on an expander should be performed as the expander is approaching its design life, which is typically 100,000 hr. If a user is interested in extending the life of their expander beyond 100,000 hr, an inspection to determine overhaul scope and to perform a remaining life analysis should be considered between 60,000 and 100,000 hr of operation, depending on overall expander condition.

TYPICAL APPLICATION AND RESULTS OF REMANENT LIFE ANALYSIS

The following information has been taken from a number of expanders that have had remanent life analysis work performed on various components. The results are presented on a component-by-component basis to illustrate the various concerns and items highlighted previously. This experience is presented as guidelines to alert the FCC expander user to potential problem areas and to aid in anticipating what may be expected when the expander remanent life analysis is performed.

The inlet temperature of the expanders under evaluation range from 1310°F to 1350°F (710°C to 732°C). The time of operation varies between 40,000 and 90,000 hr of service.

Casings. In performing a remaining life analysis, the expander casings are first visually inspected for obvious signs of wear, distortion, and distress. Particular attention is paid to the higher stressed flange regions and the fasteners holding the flanges together. After the casings are cleaned, a nondestructive inspection is performed to determine if any cracking exists. The casings are then evaluated for erosive wear, corrosion, excessive mechanical distortion, hardness, and microstructure using the previously described techniques.

Alloy steel. Alloy steel casings have been found to suffer more from oxidation problems than the stainless steel casing. A typical general oxidation type corrosion of an expander exhaust casing is shown in Figure 7. The oxide scale can be fairly heavy but rarely limits operating life.

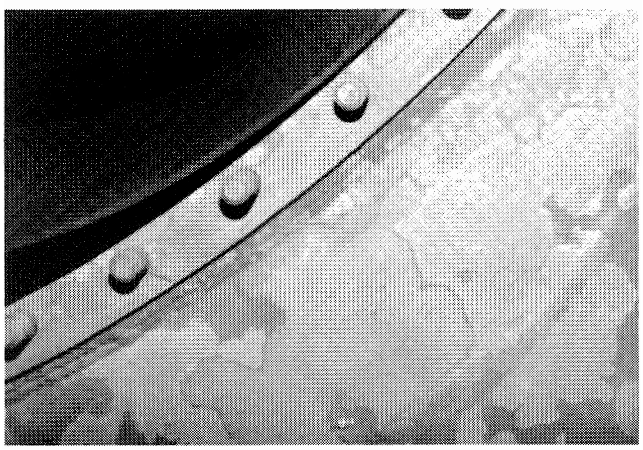

Figure 7. Typical Alloy Steel Exhaust Casing Oxidation.

Stainless steel. Austenitic stainless steel casings suffer uniquely from sigma phase embrittlement. An illustrative example of this damage, and the effect of elevated metal temperature, can be seen in Figures 8, 9, and 10. The microstructure of the material was specifically examined for evidence of sigma phase which is a strong indicator of inservice aging. The photomicrographs shown in Figure 8 are taken from the gas path side of the inlet casing, which is exposed to full inlet temperature. Note the extensive sigma phase present at the grain boundaries, comprising 10 percent to 15 percent of the area. With this level of sigma and other aging effects, this casing would be susceptible to inservice cracking and a repair welding effort would be most difficult. Impact testing of materials removed from FCC service has shown that the impact energy can degrade from an original value in excess of 200 ft-lb to less than 20 ft-lb.

In contrast to the extensive sigma phase found in the inlet casing, the same expander exhibited virtually no aging affects on the cooler discharge casings. Figure 9 is taken from the discharge region where metal temperatures are approximately 1000°F (540°C).

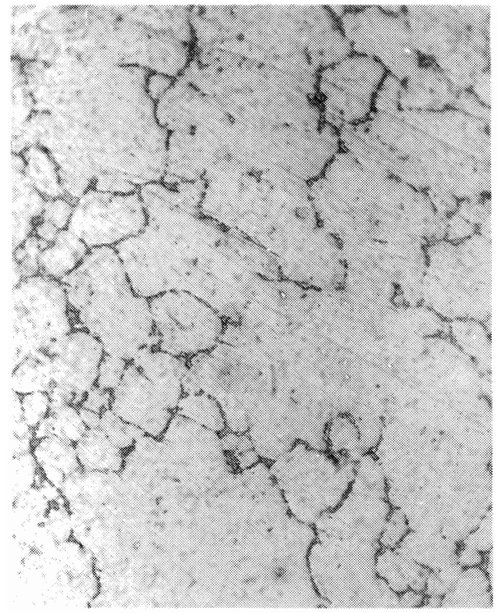

Figure 8. Inlet Casing Microstructure After 60,000 hr. Note: Severe sigma phase-400X.

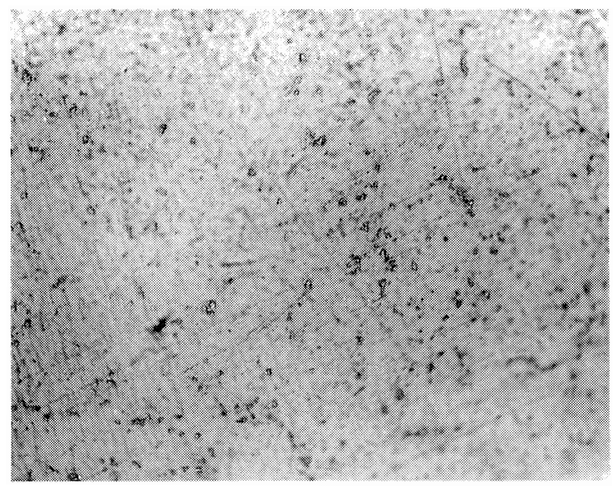

Figure 9. Exhaust Casing Microstructure After 60,000 hr. Note: Lack of sigma phase-400X.

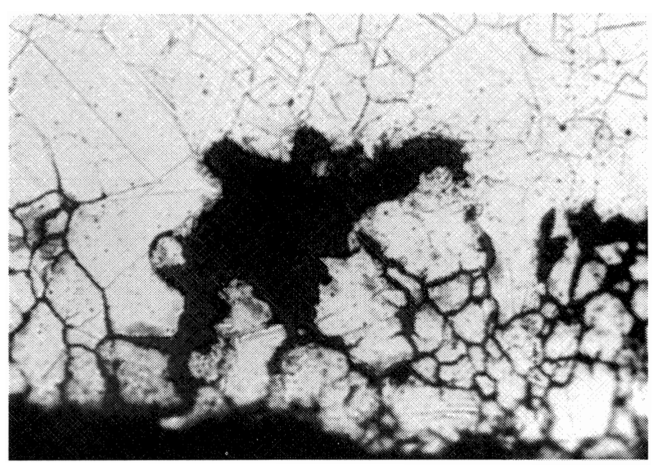

Figure 10. Nosecone Microstructure After 60,000 hr. Note: Surface oxidation.

There is little evidence of sigma phase formation. The dark regions in Figure 9 reflect a soft ferrite phase. The degree of sigma formation is very temperature dependent as is evident in this example. The temperature difference between the inlet and exhaust casings shown is approximately 300°F (170°C). The hotter inlet casing shows significant aging while the cooler exhaust casing does not.

Stationary flow path components. The expander stationary flow path components include the nosecone, shroud rings, and stator vanes. Often flow path components are retired long before high temperature aging effects result due to creep damage or erosive wear.

Nosecone. Expander nosecones are subject to the full inlet conditions of the flue gas. This component often shows the greatest amount of creep damage, inservice aging, erosion, and corrosion when compared to all other stationary components. A nosecone after 60,000 hr of operation is shown in Figure 10. It has experienced a significant amount of corrosion (oxidation) along with sigma phase embrittlement. The nosecone was found to have a significant high temperature oxide/sulfide scale over the entire surface. The corrosive scales were found to be approximately 0.015 in (0.40 mm) to 0.020 in (0.50 mm) thick. These scales would be considered heavy for the time of service and may be indicative of higher than normal operating temperatures and high flue gas sulfur levels. The amount of sigma phase present would make this nosecone very susceptible to cracking and may not allow for future repair. The sigma phase was nearly continuous throughout the grain boundaries and can be seen in Figure 10.

Stators and Shrouds

Stators. Stators experience the full inlet gas temperature and operating pressure. Since there is always a pressure drop across the stator vanes, they are subject to significant bending stresses. These bending stresses, coupled with high metal temperatures, can result in a tendency for the stators to lean by creep downstream toward the rotor.

Expander stator blades are usually retired with less than 70,000 hr due to catalyst erosion. Creep distortion and LCF cracking are readily detectable by conventional nondestructive inspection methods. For these reasons, remaining life analysis is generally not required. Remaining life analysis does come into play when the stators are repair welded or reapplied in new shroud rings. The stator blade material may suffer from a coarsening of grain boundary carbides, sigma phase embrittlement, and other phenomena that tend to reduce strength and ductility, along with reducing the weldability of the vanes. The microstructure of a Stellite 31 stator vane is shown in Figure 11 after 45,000 hr of service. Metallurgical analysis of stators is typically performed by removing material samples.

Shrouds. Like stators, shroud rings are generally retired due to erosive wear or distortion prior to the need to perform a remaining life analysis. The stainless steel materials of the shroud rings are susceptible to the same aging effects of nosecone and outer casings.

Rotor Components

The rotor disc and blades are subjected to temperatures sufficiently high to cause significant degradation in life. The temperatures are sufficient to cause material degradation in rotor blades and discs with operating times of more than 30,000 hr.

Rotor blades. Rotor blades are subjected to the highest combination of loads in the expander. They may operate at a level of stress and temperature that can produce failure by any of the mechanisms discussed previously. To withstand these conditions, expander blades are typically made from alloys that possess the greatest combination of strength, creep, and corrosion resistance. FCC expander rotor blades have been manufactured from A-286, Nimonic, Inconel X-750, Waspaloy, and IN-738.

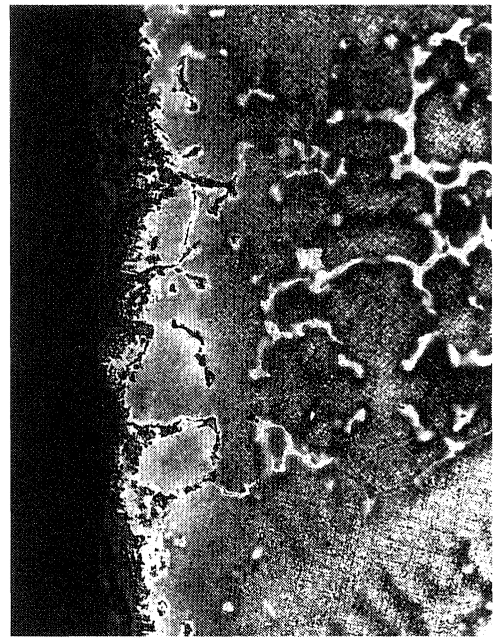

Figure 11. Stellite Stator After 45,000 hr. Note: Grain boundary precipitates.

Experience has shown that the most likely failure mechanisms for expander rotor blades are high cycle fatigue, erosion, and corrosion damage. Once a blade crack initiates, a creep or creep fatigue crack propagation is common. Creep failures are unusual since a majority of rotor blades are retired from service after 30,000 hr due to excess blade wear as the result of catalyst erosion. Several expander installations have had successful blade operating times of greater than 50,000 hr. If rotor blades are removed from service and the condition warrants them to be considered for reuse or repair, a remaining life analysis of the blades should be performed.

The rotor blades must be removed from the rotor disc to evaluate their condition, since the most critical region and most susceptible to corrosion, fretting, and creep damage is the attachment region. It is most likely that the blades will require replacement as the result of airfoil or attachment environmental degradation. Should this be the case, a remaining life analysis of the blades would not warranted. If the blades appear to be reusable or with some need of refurbishment, a remanent life analysis would be justified.

Examination of rotor blades after 50,000 hr of operation can show signs of inservice aging. If higher than normal operating temperatures have been experienced, significant grain growth and creep damage may be noted. Extensive grain growth in a Waspaloy blade is shown in Figure 12 after severe temperature excursion and the replacement of the blades was warranted.

Rotor discs. The most significant component requiring detailed remanent life analysis on an FCC expander is the rotor disc. Unlike the rotor blades, the disc(s) is reused for numerous operating campaigns and operating periods in excess of 100,000 hr are quite probable. The rotor discs must be thoroughly cleaned for a proper inspection. Conventional dimensional and non-destructive inspection techniques should be used to evaluate any erosion, corrosion, or fretting damage. It must be pointed out that an experienced inspector should be utilized since many of the corrosion products show up as only surface discolorations and can be very tenacious to remove by conventional cleaning methods. The corrosion

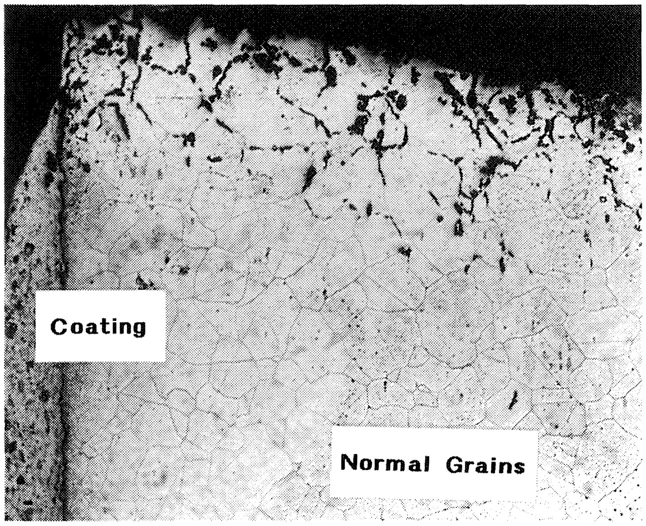

Figure 12. Waspaloy Rotor Blade Grain Growth. Note: Normal microstructure at bottom and blade coating (50X).

products can also easily be misidentified and a dangerous situation may ensue if the disc is returned to service.

Unfortunately, the most critical regions (attachment fillets) that should be examined for inservice aging or degradation are the most difficult to examine. Destructive testing is the only sure method of properly examining rotor discs remaining life capabilities. Albeit very difficult to perform, replication techniques have been found to be the most effective method in the evaluation of pit depths and microstructure in the attachment regions.

As discussed previously, no metallographic or mechanical testing techniques exist to evaluate LCF damage or remaining LCF life. Low-cycle fatigue can limit the life of expander discs. Because of the higher rim temperatures typical of power turbines, disc thermal stresses can be significant. These stresses tend to be the highest in the attachment, bore region, around tie bolt holes, and other fillet radii. Since the consequences of a disc LCF failure in the bore region could lead to a catastrophic disc burst (which is never contained) this type of evaluation should be part of any remanent life analysis. Disc evaluations and material testing are sometimes possible using boat samples. At times however, remaining disc creep and low cycle fatigue life can only be predicted through structural analysis and operational review.

SUMMARY AND CONCLUSIONS

While many remaining life analysis techniques can provide only qualitative or semiquantitative results, when used conservatively, and with experience-based engineering judgement, these techniques are a very useful aid in making decisions to extend the operating life of an expander. They should be included in making operating and overhaul decisions of any unit approaching its published design life. The lives of the critical components are often greater than the published design life or they can be extended using specialized material restoration and well established component repair techniques.

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